

Selective Electrodeposition of Nanometerscale Magnetic Wires

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A selective electrodeposition method for the fabrication of extremely thin and long metallic and magnetic wires and other nanostructures is introduced. Growth is done on the cleaved edge of a semiconductor multilayer structure incorporating a 4 nm wide modulation doped quantum well. This conducting quantum well is connected to the negative current contact during electrodeposition. Since electrodeposition requires the neutralization of positive metal ions from the solution, deposition takes place selectively onto the edge of the quantum well, leading to the fabrication of extremely thin magnetic metal wires, which should be useful for the investigation of the limits of magnetic storage.

Extremely thin magnetic and non-magnetic metal wires are of great fundamental and practical interest. The study of transport properties of extremely thin metal wires is important to clarify localization phenomena, while nanometer scale magnetic wires are of fundamental and technological relevance for the exploration of the extreme limits of magnetic storage [1]. However, the precisely controlled fabrication of smaller and smaller nanometerscale wires is extremely challenging.

Electrodeposition of ultrafine wires using templates has been first used for the fabrication of nanowires by Possin [2]. Possin fabricated short Sn, In, and Zn nanowires with diameters of 30 nm and lengths of up to 15 μ m by electrodeposition into pores fabricated by etching of the damage produced by high energy charged particles into mica [3]. Nanowires have been deposited also into the pores of electrochemically oxidized Aluminium [4], and into pores etched into plastic membranes [5]. Growth of magnetic wires into pores has been reported by AlMawlawi [6]. Electrochemical fabrication of magnetic structures has been recently reviewed by Schwarzacher and Lashmore [7]. Ultrananowire but very short structures have also been fabricated by a scanning tunneling microscope (STM) [8].

In the present work we introduce a new electrodeposition method onto a layered semiconductor template structure to fabricate nanoscale metal and magnetic wires. We report magnetic wires with a width of 20 nm, however we expect that our method should be applicable down to widths of around 4 nm, and to a variety of differently shaped structures, including closed squares in addition to straight wires. Our method greatly expands the variety of metallic and magnetic nanostructures accessible to fabrication.

The advantage of the method is that it allows the fabrication of ultrafine wires down to 4 nanometers with much more control over the shapes than is possible with growth into etched nanopores. Also it allows the controlled deposition of several millimeter long parallel nanowires onto semiconductor substrates. In addition, much longer wires can be produced than is possible in the fairly narrow range of view of an STM.

A schematic view of our fabrication method is shown in Figure 1. The basic process is electrodeposition where positively charged metal ions from a solution recombine with electrons delivered by an electrode to form neutral deposited atoms onto the same electrode. We use the edge of a conducting 4 nanometer thin InAs quantum well, embedded into a semiconductor multilayer structure, as the electrode. Thus the 4 nm wide edge of the InAs conducting quantum well acts as a template for selective electrodeposition. We use an InAs-edge because the Fermi level on the surface of InAs is pinned within the conduction band. Thus the surface depletion layer customary in GaAs-based materials is avoided. The InAs well therefore forms an extremely thin conducting layer of which one edge is exposed to the electrolyte at the cleaved edge. Here we report results on Permalloy as the deposited material, but a range of other materials are under investigation.

The following sequence of layers is grown by molecular beam epitaxy (MBE) onto an InP substrate: a 200 nm undoped $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ buffer layer (200 nm), a 13 nm n^+ Si-doped ($4 \times 10^{18} \text{ cm}^{-3}$) $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, a 6 nm undoped

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$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ spacer layer, a 4 nm undoped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ spacer layer, a 4 nm undoped InAs modulation doped channel, a 12 nm undoped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ spacer layer, a 20 nm undoped $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ spacer layer and finally a 2 nm undoped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ protective layer.

An approximately 10mm \times 15mm large chip was cleaved from the wafer. The conducting modulation doped layer was contacted at one point at one end of the cleaved chip (opposite to the end where the wire was deposited) by thermally diffusing Indium under a controlled Argon atmosphere in a reaction chamber. A thin gold wire was soldered onto the diffused Indium contact. The contacted chip was then suspended on the Gold wire into the electroplating bath. For electro-deposition this contact was connected to the negative output of a constant current source. A Nickel wire was connected to the positive output of the constant current source and inserted into a citrate-complexed nickel-iron electrolyte [9] with a pH of around 4.5. The container of the plating bath was temperature stabilized to $(29.2 \pm 0.5)^\circ\text{C}$. Typically currents of 100 μA were used. The fabricated metal wires were investigated using an atomic force microscope (AFM). Figure 2 shows an AFM image of the top view of the cleavage plane of the wafer with a 20 nm permalloy wire. Starting from the left hand side, first the edge of the wafer is seen, and then close to it the permalloy wire. In addition to the wire, several approximately 20 nm large spherical particles are also detected. The origin of these particles is unknown. The contrast between the 261 nm MBE deposited multilayer structure and the substrate can also be seen on the AFM image.

In conclusion, we have introduced and demonstrated a new fabrication method for the selective deposition of extremely thin metallic wires. We have demonstrated the deposition of a 20 nm permalloy wire. The present method should also allow the deposition of wires down to widths of about 4 nm, enabling the fabrication of a rich variety of structures. The present method has many advantages compared to competing methods: for example it enables the fabrication of millimeter long wires. We expect the present method to be of great use for the exploration of the magnetic properties of metallic nanostructures, and possibly even for the fabrication of novel magnetic storage or read/write devices.

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FIG. 1. This schematic drawing shows a new method of selective electrodeposition using the cleaved edge of a conducting 4 nm InAs modulation doped quantum well embedded into a layered semiconductor structure as a template. This conducting InAs quantum well is connected to the negative current contact during electrodeposition, leading to the selective growth of an extremely thin magnetic metal wire.

FIG. 2. Atomic force microscope image of a 20 nm thin magnetic wire deposited onto the cleaved edge of an MBE grown multilayer structure. In addition to the desired wire structure, several undesired spherical particles can also be observed. The contrast between the 261 nm thick MBE multilayer structure and the substrate can also be seen in the AFM image.